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A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems

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ABSTRACT

Recently scientists used nanoparticles in refrigeration systems because of theirs remarkable improvement in thermo-physical, and heat transfer capabilities to enhance the efficiency and reliability of refrigeration and air conditioning system. In this paper thermal–physical properties of nanoparticles suspended in refrigerant and lubricating oil of refrigerating systems were reviewed. Heat transfer performance of different nanorefrigerants with varying concentrations was reviewed and review results are presented as well. Pressure drop and pumping power of a refrigeration system with nanorefrigerants were obtained from different sources and reported in this review. Along with these, pool boiling heat transfer performance of CNT refrigerant was reported.

Moreover, challenges and future direction of nanofluids/nanorefrigerants have been reviewed and presented in this paper. Based on results available in the literatures, it has been found that nanorefrigerants have a much higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional refrigerant. This can be considered as one of the key parameters for enhanced performance for refrigeration and air conditioning systems. Because of its superior thermal performances, latest upto date literatures on this property has been summarized and presented in this paper as well.

The results indicate that HFC134a and mineral oil with TiO_2 nanoparticles works normally and safely in the refrigerator with better performance. The energy consumption of the HFC134a refrigerant using mineral oil and nanoparticles mixture as lubricant saved 26.1% energy with 0.1% mass fraction TiO_2 nanoparticles compared to the HFC134a and POE oil system. It was identified that fundamental properties (i.e. density, specific heat capacity, and surface tension) of nanorefrigerants were not experimentally determined yet. It may be noted as well that few barriers and challenges those have been identified in this review must be addressed carefully before it can be fully implemented in refrigeration and air conditioning systems.

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1. Introduction

Nanofluids are a relatively new class of fluids which consist of a base fluid with nano-sized particles (1–100 nm) suspended within them. These particles, generally a metal or metal oxide, increase conduction and convection coefficients, allowing for more heat transfer out of the coolant [1]. Serrano et al. [2] provided excellent examples of nanometer in comparison with millimeter and micrometer to understand clearly as can be seen in Fig. 1.

In the past few decades, rapid advances in nanotechnology have lead to emerging of new generation of heat transfer fluids called "nanofluids". Nanofluids are defined as suspension of nanoparticles in a basefluid. Some typical nanofluids are ethylene glycol based copper nanofluids, water based copper oxide nanofluids, etc. Nanofluids are dilute suspensions of functionalized nanoparticles composite materials developed about a decade ago with the specific aim of increasing the thermal conductivity of heat transfer fluids, which have now evolved into a promising nanotechnological area. Such thermal nanofluids for heat transfer applications represent a class of its own difference from conventional colloids for other applications. Compared to conventional solid–liquid suspensions for heat transfer intensifications, nanofluids possess the following advantages [1]:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
- Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

Recently scientists used nanoparticles in refrigeration systems because of its remarkable improvement in thermo-physical, and heat transfer capabilities to enhance the efficiency and reliability of refrigeration and air conditioning system. Elcock [3] found that TiO_2 nanoparticles can be used as additives to enhance the solubility of the mineral oil with the hydrofluorocarbon (HFC) refrigerant. Authors also reported that refrigeration systems using a mixture of HFC134a and mineral oil with TiO_2 nanoparticles appear to give better performance by returning more lubricant oil to the compressor with similar performance to systems using HFC134a and POE oil. Hindawi [4] carried out an experimental study on the boiling heat transfer characteristics of R22 refrigerant with Al_2O_3 nanoparticles and found that the nanoparticles enhanced the refrigerant heat transfer characteristics with reduced bubble sizes.

Eastman et al. [5] investigated the pool boiling heat transfer characteristics of R11 refrigerant with TiO_2 nanoparticles and showed that the heat transfer enhancement reached 20% at a particle loading of 0.01 g/L. Liu et al. [6] investigated the effects of carbon nanotubes (CNTs) on the nucleate boiling heat transfer of R123 and HFC134a refrigerants. Authors reported that CNTs increase the nucleate boiling heat transfer coefficients for these refrigerants. Authors noticed large enhancements of up to 36.6% at low heat fluxes of less than 30 kW/m^2. Thus, the use of nanoparticles in refrigeration systems is a new, innovative way to enhance the efficiency and reliability in the refrigeration system.

In the literatures a number of reviews on thermal and rheological properties, different modes of heat transfer of nanofluids have been reported by many researchers [7–10]. However, to the best of authors' knowledge, there is no comprehensive literature on the nanoparticles as additives with conventional refrigerants and oils used in refrigeration system. It is authors' hope that this review will be useful to fill identified research gaps and to overcome the challenges of nanorefrigerants.

2. Thermal conductivity of nanoparticles used in refrigerants

Different concentrations of nanoparticles of CuO, Al_2O_3, SiO_2 diamond, CNT, TiO_2 were used in base refrigerants such as R11, R113, R123, R134a, and 141b as found in the available literatures

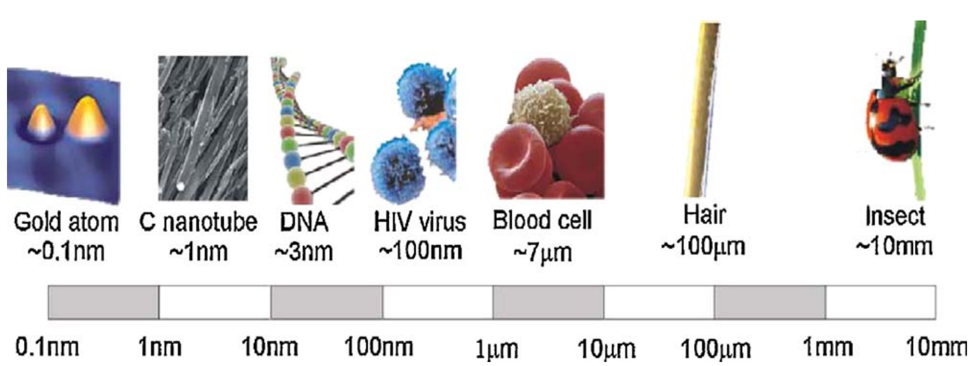

Fig. 1. Length scale and some examples related [2].

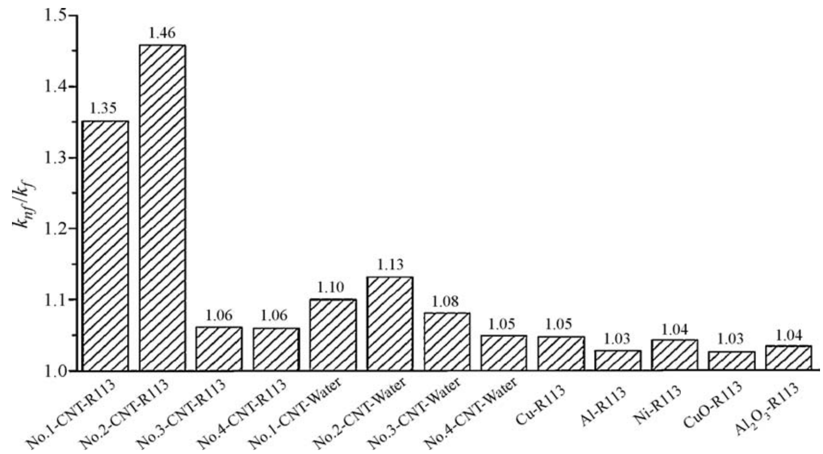

Fig. 2. Comparison of k_{nf}/k_f among CNT–R113, CNT–water and spherical-particle-R113 [11]. k_{nf}, thermal conductivity of nanofluid; k_f, thermal conductivity of pure fluid.

[11–23]. Thermal conductivity enhancement of some refrigerants with nanoparticles is shown in Figs. 2–4.

The nanofluid is a new type of heat transfer fluid by suspending nano-scale materials in a conventional host fluid and has higher thermal conductivity than the conventional host fluid. The nanorefrigerant is one kind of nanofluid and its host fluid is a refrigerant. A nanorefrigerant has higher heat transfer coefficient than the host refrigerant and it can be used to improve the performance of refrigeration systems. The heat transfer coefficient of a fluid with higher thermal conductivity is larger than that of a fluid with lower thermal conductivity if the Nusselt numbers of them are the same. Therefore, researches on improving thermal conductivities of nanorefrigerants are necessary. There are two methods to improve the thermal conductivity of a nanorefrigerant. The first one is to increase the volume fraction of nano-scale materials in the nanorefrigerant, and the second one is to use nano-scale materials with high thermal conductivity [11].

The experimental results by Jiang et al. [11] showed that the thermal conductivities of carbon nanotube (CNT) nanorefrigerants are much higher than those of CNT–water nanofluids or spherical-nanoparticle–R113 nanorefrigerants. Authors reported that the smaller the diameter of CNT is or the larger the aspect ratio of CNT is, the larger the thermal conductivity enhancement of CNT nanorefrigerant is as can be seen in Fig. 3.

Fig. 4 shows the comparison between the experimental data and the predicted results of the modified Yu–Choi model on CNT with refrigerants. The mean and maximum deviations of the modified Yu–Choi model are 5.5% and 15.8%, respectively, which shows that the modified Yu–Choi model is better than the existing models in predicting thermal conductivities of CNT nanorefrigerants.

3. Thermal conductivities of nanofluids

Thermal conductivity of nanofluids found to be an attracting characteristic for many applications including refrigeration and air conditioning. It represents the ability of material to conduct or transmit heat. Considerable researches have been carried out on this topic. It may be mentioned that it is a driving factor that leads to an idea of considering nanofluids as refrigerant. Eastman et al. [24] found that thermal conductivity of 0.3% copper nanoparticles of ethylene glycol nanofluids is increased up to 40% compared to basefluid. Authors stressed that, this property plays an important role in construction of energy efficient heat transfer equipment. Liu et al. [6] investigated the thermal conductivity of copper–water nanofluids produced by chemical reduction method. Results showed 23.8% improvement at 0.1% volume fraction of copper particles. Higher thermal conductivity and larger surface area of copper nanoparticles are attributed to this improvement. It is also noted that thermal conductivity increases with particles volume fraction but decreases with elapsed time. Hwang et al. [25] suggested that thermal conductivity enhancement of nanofluids is greatly influenced by thermal conductivity of nanoparticles and basefluid. For instance, thermal conductivity of water based nanofluids with multiwalled carbon nanotube have noticeably

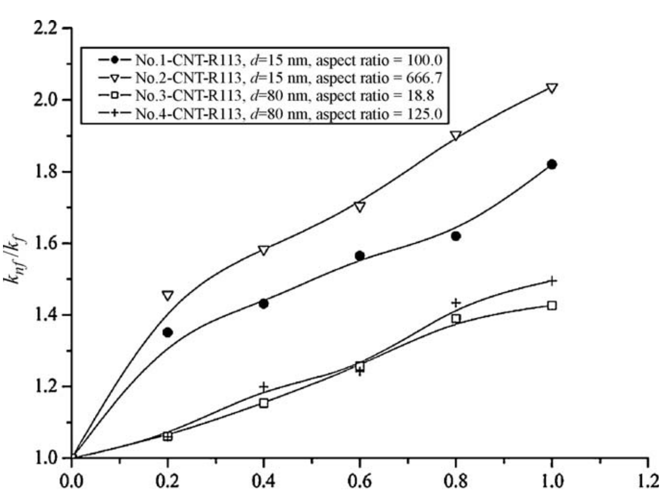

Fig. 3. Effective thermal conductivity of different concentrations of CNT [11].

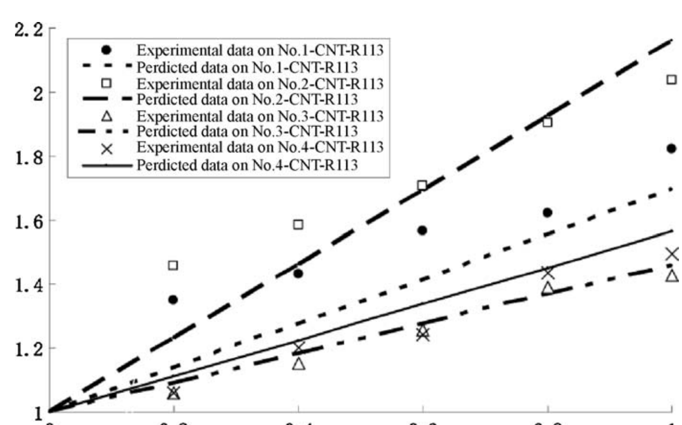

Fig. 4. Experimental data versus predicted data of the modified Yu–Choi model [11].

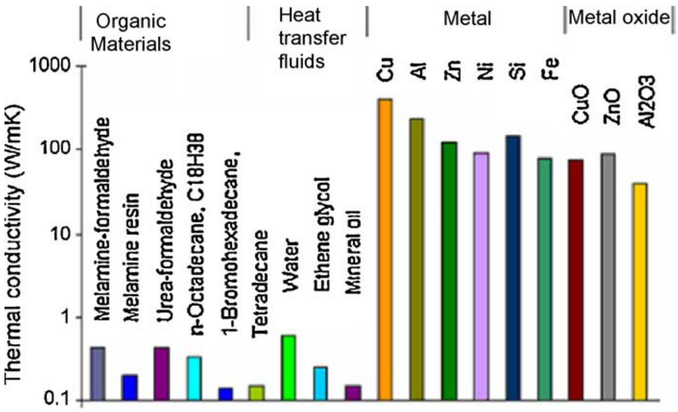

Fig. 5. Comparison of the thermal conductivity of common liquids, polymers and solids [40].

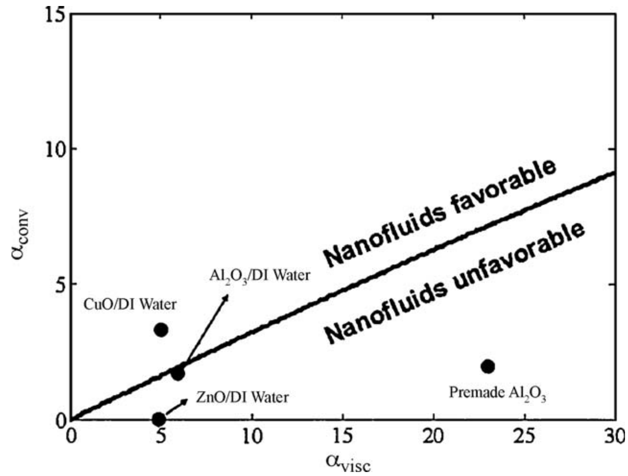

Fig. 6. The data summary of oxide nanofluids and the boundary line of nanofluid effectiveness [20].

higher thermal conductivity compared to SiO_2 nanoparticles in the same basefluid. However, Yoo et al. [26] argued that surface to volume ratio of nanoparticles is a dominant factor that influences the nanofluids thermal conductivity rather than nanoparticles thermal conductivity. Surface to volume ratio is increased with smaller sizes of nanoparticles.

Choi et al. [27] reported a 150% thermal conductivity enhancement of poly (α-olefin) oil with the addition of multi-walled carbon nanotubes (MWCNT) at 1% volume fraction. Similarly, Yang [28] reported a 200% thermal conductivity enhancement for poly (α-olefin) oil containing 0.35% (v/v) MWCNT. It is important to note that this thermal conductivity enhancement was accompanied by a three order of magnitude increase in viscosity. Eastman et al. [24] found a 40% thermal conductivity enhancement for ethylene glycol with 0.3% (v/v) copper nanoparticles (10 nm diameter), although the authors added about 1% (v/v) thioglycolic acid to aid in the dispersion of the nanoparticles. The addition of this dispersant yielded a greater thermal conductivity than the same concentration of nanoparticles in the ethylene glycol without the dispersant. Jana et al. [29] measured the thermal conductivity of a similar copper containing nanofluid, except the base fluid was water and laurate salt was used as a dispersant. Authors observed a 70% thermal conductivity enhancement for 0.3% (v/v) cu nanoparticles in water. Kang et al. [30] reported a 75% thermal conductivity enhancement for ethylene glycol with 1.2% (v/v) diamond nanoparticles between 30 and 50 nm in diameter. Despite these remarkable results, some researchers have measured the thermal conductivity of nanofluids and have found no anomalous results. Also, those results can often be predicted by conventional thermal conductivity models [31–34].

Lee et al. [35] revealed thermal conductivity of nanofluids is affected by pH level and addition of surfactant during nanofluids preparation stage. Better dispersion of nanoparticles is achieved with addition of surfactant such as sodium dodecylbenzenesulfonate. Optimum combination of pH and surfactant leads to 10.7% thermal conductivity enhancement of 0.1% Cu/H_2O nanofluids. Thermal conductivity of ethylene glycol based ZnO nanofluids measured by transient short hot wire technique is found to be increased non-linearly with nanoparticles volume fraction [36]. Jiang et al. [11] added that thermal conductivity of nanofluids also depend on the nanoparticles size and temperature. Vajjha and Das [37] also agreed that thermal conductivity is dependent not only on the nanoparticles concentration but also on the temperature. Authors concluded that, it will be more beneficial if nanofluids are used in high temperature applications.

It has been noticed that most authors agreed that nanofluids provide higher thermal conductivity compared to basefluids. Its value increases with particles concentration. Temperature, particles size, dispersion and stability do play important role in determining thermal conductivity of nanofluids [38]. Fig. 5 shows the comparison of thermal conductivity of heat transfer fluids and nanofluids. Fig. 6 shows the thermal conductivity of nanofluids at different temperatures. Table 1 also shows the enhanced thermal conductivities of metallic and non-metallic nanofluids as reported

Table 1
Summary of literature review for thermal conductivity of nanofluids [39].

	Particle	Base fluid	Average particle size	Volume fraction	Thermal conductivity enhancement	References
Metallic nanofluids	Cu	Ethylene glycol	10 nm	0.3%	40%	[42]
	Cu	Water	100 nm	7.5%	78%	[44]
	Fe	Ethylene glycol	10 nm	0.55%	18%	[45]
	Au	Water	10–20 nm	0.026%	21%	[45]
	Ag	Water	60–80 nm	0.001%	17%	[46]
Non-metallic nanofluids	Al_2O_3	Water	13 nm	4.3%	30%	[47]
	Al_2O_3	Water	33 nm	4.3%	15%	[48]
	Al_2O_3	Water	68 nm	5%	21%	[49]
	CuO	Water	36 nm	3.4%	12%	[48]
	CuO	Water	50 nm	0.4%	17%	[50]
	SiC	Water	26 nm	4.2%	16%	[49]
	TiO_2	Water	15 nm	5%	30%	[51]
	MWCNT	Synthetic oil	25 nm in diameter 50 μm in length	1%	150%	[27]
	MWCNT	Decene/ethylene glycol/water	15 nm in diameter 30 μm in length	1%	20%/13%/7%	[52]
	MWCNT	Water	100 nm in diameter 70 μm in length	0.6%	38%	[53]

Table 2
Summary of research on nanoparticles and refrigerants.

Year	Investigator	Refrigerant	Nanoparticles	Size of nanoparticles	% volume concentrations	Performance
2007	[13]	R123, R134a	Carbon nanotubes	20nm $\times$ 1 μm	1.0%	Heat transfer coefficient enhancement up to 36.6%
2009	[8]	R141b	TiO_2	21nm	0.01%, 0.03%, 0.05%	Nucleate pool boiling heat transfer deteriorated with increasing particle concentrations
2009	[54]	R113	CuO	40nm	0.15–1.5%	Maximum enhancement of heat transfer coefficient, 29.7%
2009	[61]	R134a	CuO	30nm	0.5%, 1.0%, 2.0%	
2009	[62]	R113	CuO	40 nm	0, 0.1%, 0.2%, 0.5%	Frictional pressure drop increased by 20.8%
2009	[63]	R134a	CuO	30nm	0.5%	Enhancement of heat transfer coefficient of between 50% and 275%
2010	[56]	R113	Diamond	10 nm	0–0.05%	Nucleate pool boiling heat transfer coefficient increased by 63.4%
2006	[64]	134a	TiO_2	–	–	Reduction in energy consumption by 7.43%
2010	[59]	R134a	CuO		–	No significant pressure drop, Heat transfer coefficient increased by more than 100%
	[65]	NH_3/H_2O	Al_2O_3/CNT		0.06%/0.08%	Heat transfer rate was 20% higher than those without nanoparticles

by Ref. [39]. Table 2 shows the thermal conductivity ratio (i.e. thermal conductivity of solid to liquids) of nanofluids. The ratios are found to be in the range of 3–17,100. This shows an indication that when solid particles are added in conventional liquids/coolants, thermal conductivity can be increased tremendously.

Research has shown that the thermal conductivity and the convection heat transfer coefficient of the fluid can be largely enhanced by suspended nanoparticles. Choi et al., Choi, Xuan and Roetzel, Choi et al. [1,27,41–43] observed that the thermal conductivity of this nanofluid was 150% greater than that of the oil alone. Table 1 shows the thermal performances of different types (metallic, non-metallic, MWCNT) and concentrations of nanofluids.

The enhanced thermal conductivity of nanofluids offer several benefits such as higher cooling rates, decreased pumping power needs, smaller and lighter cooling systems, reduced inventory of heat transfer fluids, reduced friction coefficients, and improved wear resistance. Those benefits make nanofluids promising for applications like refrigerants, coolants, lubricants, hydraulic fluids, and metal cutting fluids.

Fig. 6 shows the boundary of properties of nanofluids for different applications.

4. Pool boiling heat transfer performance

The phase change heat transfer characteristics of the refrigerant-based nanofluids in the heat exchangers, especially in the evaporator, is an important factor to consider. In order to investigate the overall performance of the heat exchangers of refrigeration systems using refrigerant-based nanofluids, the heat transfer characteristics of them must be known. It is reported that the concentration of nanoparticles in nanorefrigerant has influence on the boiling heat transfer coefficient as the thermo-physical properties, influence the boiling heat transfer coefficient such as thermal conductivity and viscosity and they change with the change of concentration of nanoparticles in the base fluid [1,6,14,15,20,45,54].

The researches on the boiling heat transfer characteristics of refrigerant-based nanofluids are focused on the pool boiling heat transfer [8,12,13,55] and there are no notable published researches on the flowing boiling heat transfer characteristics of refrigerant-based nanofluids.

Park and Jung [12,13] investigated the pool boiling heat transfer of CNTs (carbon nanotubes)–R22, CNTs–R123 and CNTs–R134a nanofluids on a horizontal smooth tube and found that CNTs enhanced the pool boiling heat transfer coefficients of refrigerants. Authors also reported that the enhancement became more pronounced at lower heat flux and the maximum enhancement could reach 36.6%.

Wu et al. [55] observed that the pool boiling heat transfer was enhanced at low nanoparticles concentration of TiO_2 in R11 but deteriorated under the condition of high nanoparticles concentration. Trisaksri and Wongwises [8] investigated TiO_2 in HCFC 1416 in a cylindrical copper tube and found that the nucleate pool boiling heat transfer deteriorated with increasing nanoparticle concentrations especially at higher heat fluxes. Researches on the boiling heat transfer characteristics showed that the type of nanoparticles or fluid, the nanoparticles concentration, the heat flux and the type of heating surface have influences on the nucleate boiling heat transfer of nanofluids [14,15–21,23]. Das et al. [14] reported that pool boiling performance is deteriorated at all levels of nanoparticle concentrations because of change in surface characteristics due to deposition of nanoparticles. Bang and Chang [21] also reported that boiling performance of nanofluids deteriorates. Vassallo et al. [20] reported that no enhancement in nucleate boiling with silica–water nanofluid. Vassallo et al. [20] conducted an experiment with different concentration of alumina nanoparticles with water and found that pool boiling performance is deteriorated.

The pool boiling heat transfer characteristics of refrigerant-based nanofluids is different from the flow boiling heat transfer characteristics and the pool boiling heat transfer characteristics only cannot represent the influence of nanoparticles on the heat transfer of refrigerant-based nanofluid inside heat exchanger tube in the evaporator. Thus it has become necessary to investigate flow boiling heat transfer characteristics using refrigerant-based nanofluids as the working fluid. There are correlations existing to predict heat transfer coefficient of pure refrigerant flow boiling inside the horizontal smooth tube, but they are not developed yet to predict the heat transfer coefficient of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube to design a heat exchanger using refrigerant-based nanofluid as the working fluid.

Hao et al. [54] investigated the heat transfer characteristics of refrigerant-based nanofluids flow boiling inside a smooth tube at different nanoparticles concentration, mass fluxes, heat fluxes, and inlet vapor qualities to analyze the influence of nanoparticles on the heat transfer characteristics of refrigerant-based nanofluid flow boiling inside the smooth tube. Authors used average 40 nm diameter of CuO nanoparticles and Transmission Electron Microscope [33] was used to identify the images. Mass fractions being considered as 0.1%, 0.2% and 0.5% and ultrasonic vibration was used to stabilize the dispersion of nanoparticles. Surfactant was not being added to improve the dispersion and stability of nanofluid as it has influence on the heat transfer characteristics of

the nanofluid [8,14] and may cause the sorption and agglutination phenomenon of the nanofluid during boiling heat transfer process [8].

Hao et al. [54] have presented a correlation for predicting the heat transfer coefficient of refrigerant-based nanofluid and the predicted heat transfer coefficients agree with 93% of the experimental data within the deviations of ±20%. Authors observed that the heat transfer coefficient of refrigerant-based nanofluid in flow boiling is larger than that of pure refrigerant and the maximum enhancement is about 29.7% when observed with a mass fraction of nanoparticles 0–0.5 wt%. Authors have reported that the reduction of the boundary layer height due to the disturbance of nanoparticles enhances the heat transfer. Wu et al. [55] and Vassallo et al. [20] observed boundary layer height is reduced by the disturbance of nanoparticles and the flow boiling heat transfer of refrigerant-based nanofluid is enhanced.

Hao et al. [54] investigated experimentally and numerically the migration characteristics of nanoparticles in pool boiling process of nanorefrigerant and nanorefrigerant–oil mixture. Authors have used R113 as the base fluid, CuO the nanoparticles and RB68EP as the lubricant oil. Authors observed that the migrated mass of nanoparticles in the pool boiling process of both nanorefrigerant and nanorefrigerant–oil mixture, increase with the increase of the original mass of nanoparticles and the mass of refrigerant. The migration ratio decreases with the increase of volume fraction of nanoparticles. Authors also reported that the migration mass of nanoparticles and migration ratio in the nanorefrigerant are larger than those in the nanorefrigerant–oil mixture. The migrated mass of nanoparticles in the nanorefrigerant is 17.5% larger than that in the nanorefrigerant–oil mixture on the average under the conditions of investigation. However they developed a numerical model where predictions and experimental data were in the range of 7.7–38.4%.

Hao et al. [56] studied experimentally the nucleate pool boiling heat transfer characteristics of refrigerant/oil mixture with diamond nanoparticles. The refrigerant was R113 and the oil was VG68. The results indicate that the nucleate pool boiling heat transfer coefficient of R113/oil mixture with diamond nanoparticles is larger than that of R113/oil mixture by maximum of 63.4% and the enhancement increases with the increase of nanoparticles concentration in the nanoparticles/oil suspension and decreases with the increase of lubricating oil concentration. Authors developed a correlation for predicting the nucleate pool boiling heat transfer coefficient of refrigerant/oil mixture with nanoparticles and it agrees well with the experimental data of refrigerant/oil mixture with nanoparticles.

Wang et al. [57] carried out an experimental study of the boiling heat transfer characteristics of R22 refrigerant with Al_2O_3 nanoparticles and found that the nanoparticles enhanced the refrigerant heat transfer characteristics with reduced bubble sizes that moved quickly near the heat transfer surface.

Li et al. [58] investigated the pool boiling heat transfer characteristics of R11 refrigerant with TiO_2 nanoparticles and showed that the heat transfer enhancement reached 20% at a particle loading of 0.01 g/L. Fu et al. [59] reported that nanoparticles may be effective to enhance the heat transfer of the refrigerant and improving the property of the mineral oil. One nanolubricant – a lubricant for chillers that incorporates a dispersion of nanometer-sized particles – has already been shown to improve the boiling heat flux by nearly 300% compared to the original nanoparticle-free refrigerant [60]. Table 2 shows summary of heat transfer enhancement reported by many researchers.

Peng et al. [62] investigated the influence of nanoparticles on the heat transfer characteristics of refrigerant-based nanofluids flow boiling inside a horizontal smooth tube, and presented a correlation for predicting heat transfer performance of refrigerant-based nanofluids. For the convenience of preparing refrigerant-based nanofluids, R113 refrigerant and CuO nanoparticles were used by the authors. Authors reported that the heat transfer coefficient of refrigerant-based nanofluids is higher than that of pure refrigerant, and the maximum enhancement of heat transfer coefficient found to be about 29.7%. Naphon et al. [66] reported that the heat pipe with 0.1% nanoparticles concentration gave efficiency 1.40 times higher than that with pure refrigerant as can be seen in Fig. 7 and Fig. 8 shows heat transfer enhancement of nanorefrigerants.

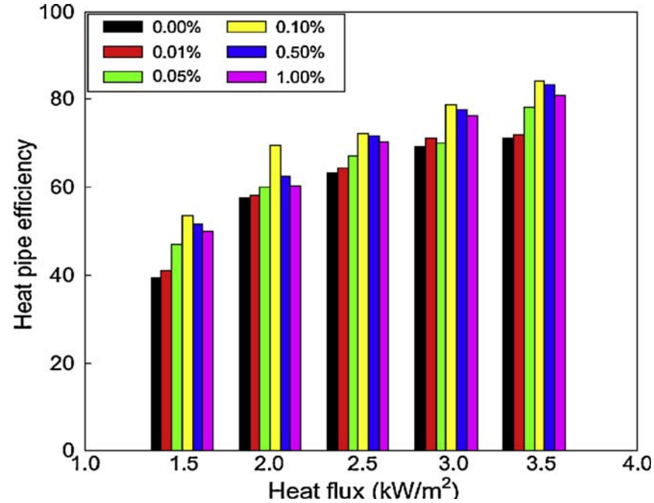

Fig. 7. Effect of nanoparticles concentrations on the heat pipe efficiency [67].

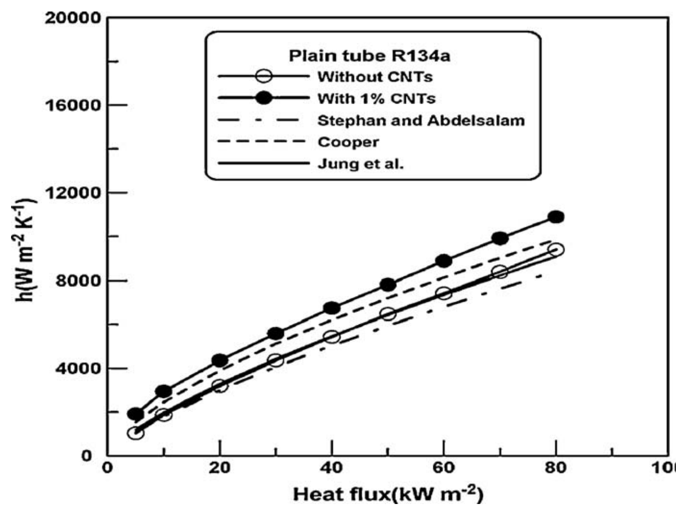

Fig. 8. Boiling heat transfer coefficients with 1.0 vol% CNTs for R134a [13].

Heat pipe technology has been used in wide variety of applications in the various heat transfer devices especially in the electronic components. However, the heat transfer capability is limited by the working fluid transport properties. The basic idea is to enhance the heat transfer by changing the fluid transport properties and flow features with nanoparticles suspended. New experimental data on the efficiency enhancement of heat pipe with nanofluids are presented by Ref. [66]. Effects of nanoparticles concentrations on the heat pipe efficiency were investigated and obtained the optimum condition that results in maximum efficiency [66].

5. Lubricity and material compatibility

A few investigations were carried out with nanoparticles in refrigeration systems to use advantageous properties of

Table 3
Material compatibility results for TiO_2 nanoparticles compared to tests with POE oil 10 denotes HFC143a and mineral oil without nanoparticles.

Sample	Dimension changes (%)				Weight changes (%)			
	POE	0	0.04%	0.06%	POE	0	0.04%	0.06%
PTFE	1.397	1.330	1.212	0.535	−0.448	0.064	0.664	0.226
PET	0.264	2.155	2.976	0.559	11.171	1.563	1.563	−2.963
Lead wire	−0.039	0.761	0.244	0.369				
Tie cord	−0.671	0.990	5.000	1.163				
Rubber	−2.132	104.459	3.424	6.663				

nanoparticles to enhance the efficiency and reliability of refrigerators. For example, Wang and Xie [68] found that TiO_2 nanoparticles can be used as additives to enhance the solubility of the mineral oil in the hydrofluorocarbon (HFC) refrigerant. In addition, refrigeration systems using a mixture of HFC134a and mineral oil with TiO_2 nanoparticles appear to give better performance by returning more lubricant oil back to the compressor compared to systems using HFC134a and POE oil.

A refrigerator performance with the nanoparticles was investigated by Refs. [64,69]. Authors reported that HFC134a and mineral oil with TiO_2 nanoparticles work normally and safely in a refrigerator. The refrigerator's energy performance was better than the HFC134a and POE oil system.

Fu et al. [59] reported that nanoparticles may be effective to improve the property of the mineral oil. Table 3 provides a summary of the results with the TiO_2 nanoparticles with 0.04% and 0.06% mass fractions. The dimensions and mass changes of the materials listed in table indicate that the HFC134a and the mineral oil with TiO_2 nanoparticles are compatible with the refrigeration system materials. The material compatibility is comparable to results with HFC134a and POE oil. Bi et al. [69] reported that the nanoparticles enhance the solubility of the HFC134a and mineral oil.

Peng et al. [62] discussed the replacement of the R134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant. The mineral lubricant with Al_2O_3 nanoparticles (0.05, 0.1, and 0.2 wt%) was used to improve the lubrication and heat transfer performance. Experimental results indicated that the 60% R134a and 0.1 wt% Al_2O_3 nanoparticles were optimal. Under these conditions, the power consumption was reduced by 2.4%, and the coefficient of performance was increased by 4.4%. These results show that replacing R134a refrigerant with hydrocarbon refrigerant and adding Al_2O_3 nanoparticles to the lubricant effectively reduced power consumption.

Lee et al. [70] presents the friction and antiwear characteristics of nano-oil composed of refrigerator oil and fullerene nanoparticles in the sliding thrust bearing of scroll compressors. The friction coefficient of fullerene nano-oil at the lower normal loads (∼1200 N) under the fixed orbiting speed (∼1800 rpm) was ∼0.02 while that of pure oil was ∼0.03, indicating that that the fullerene nanoparticles dispersed in the base refrigerant oil improved the lubrication property by coating the friction surfaces. However the differences between friction coefficients for both nano-oil and pure oil were found to be negligible at higher normal loads conditions (>∼1200N), indicating that the nanoparticles in the base oil have little effect on the enhancement of lubrication between the friction surfaces. The friction coefficient of nano-oil at various speeds of the orbiting plate in the sliding thrust bearing was found to be less than that of pure oil over the entire orbiting speed ranging between 300 and 3000 rpm. This is presumably because fullerene nanoparticles, which were inserted between the friction surfaces, improved the lubricating performance by increasing the lubricant oil viscosity and simultaneously preventing direct metal surface contacts [71].

The tribological properties of fullerene nanoparticles-added mineral oil were investigated as a function of volume concentration of fullerene nanoparticle additives (e.g., 0.01, 0.05, 0.1, and 0.5 vol%) by Ref. [72]. The lubrication tests were performed at the disk-on-disk type tester under the various normal forces and fullerene volume concentrations. Tribological properties were evaluated by measuring the friction surface temperature and friction coefficient. Authors reported that the nano-oil containing the higher volume concentration of fullerene nanoparticles resulted in the lower friction coefficient and less wear in the fixed plate, indicating that the increase of fullerene nanoparticle additives improved the lubrication properties of regular mineral oil.

The friction coefficient of nano-oil IV was found to be ∼0.02, which is the lowest friction coefficient among various nano-oils studied by Ref. [72]. Therefore, it can be stated that oil with more fullerene nanoparticle additives shows enhanced lubrication property [72], see Fig. 9 below.

Fig. 10 shows the Stribeck curve measured for raw mineral oil, nano-oil I, II, III, and IV. It was noted that the friction coefficients of all oils were not appreciably changed up to the normal force of 200 N. However, when the normal force increased beyond 200 N, the viscosity was decreased by increasing oil temperature due to local metal-to-metal contact between the plates. One can see that the maximum friction coefficients were decreased as the fullerene volume fraction was increased. This is presumably attributed to (i) the added fullerene molecules accelerate self-restoration of the polymeric tribofilm damaged in the course of mechanochemical degradation, and also (ii) the fullerene particles with a spherical structure play a role of ball bearing in the friction surfaces [72].

Authors reported that the amount of scratched circles was decreased with increasing the volume concentration of the

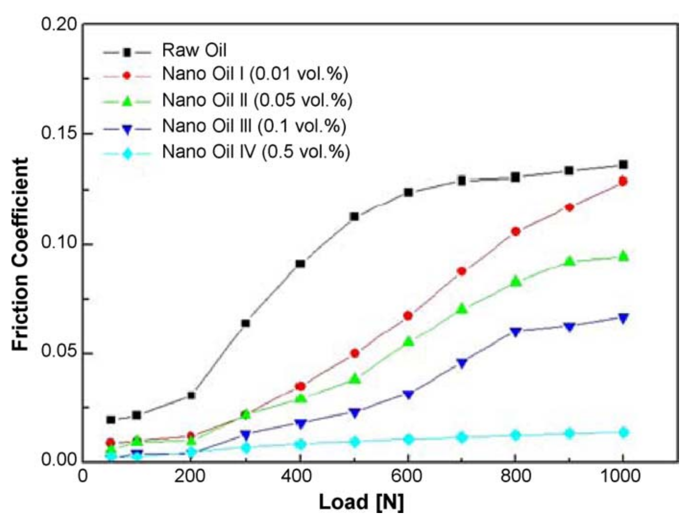

Fig. 9. Lubrication test results on the friction coefficient as a function of the fullerene volume fraction of nano-oil using the disk-on-disk type tester at the rotating speed of 1000 rpm [72].

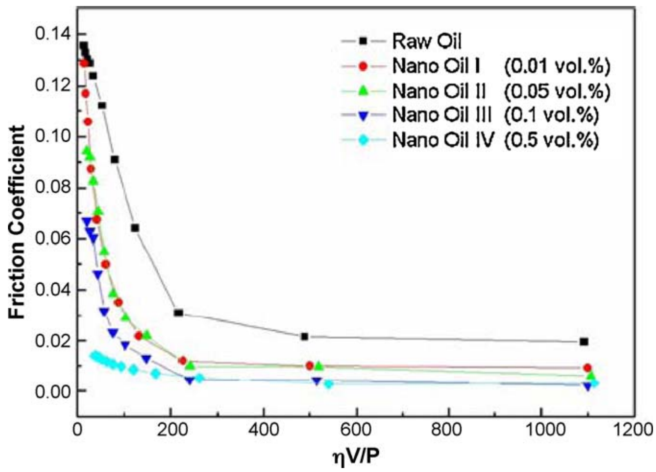

Fig. 10. Relationship between and the friction coefficients as a function of the fullerene volume fraction of nano-oils.

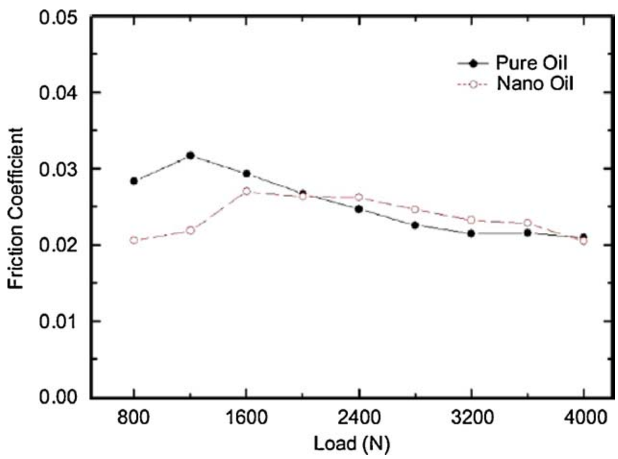

Fig. 11. Lubrication test results on the friction coefficient as a function of the normal axial force in the sliding thrust bearing tester at the fixed orbiting speed of 1800 rpm for the cases of pure oil and 0.1 vol% nano-oil [70].

fullerene suspension. It indirectly indicates that the nano-oil IV, which has the highest volume concentration (~0.5 vol%) in nano-oils employed in this study, performs the best lubrication than raw mineral oil and nano-oil I, II, and III at the same friction conditions.

Fig. 11 shows that the friction coefficient (i.e. 0.02) of carbon nano-oil is less than the friction coefficient of pure oil (i.e. 0.03) at 1200 N. This indicates that less metal contacts appear to occur with the presence of nanoparticles in the oil suspension [70].

Lee et al. [71] applied nanoparticles to oil with lower viscosity to the compressor used in a refrigerator to decrease the friction coefficient with the same or superior load-carrying capacity. Mineral oil of 8 mm^2/s was used and mixed with fullerene nanoparticles of 0.1 vol%. Friction coefficient was evaluated by a disk-on-disk tribotester. Authors reported that the friction coefficient of the nano-oil was decreased by 90% compared to pure mineral oil. As a result, authors concluded that nano-oil improves the efficiency and reliability of the compressor.

Nano-oil I shows a similar result to nano-oil II, but as the load gets heavier, the friction coefficient becomes higher. Fig. 12 shows the results for friction coefficient in the steady state as a function of normal force. In the case of mineral oil, the friction coefficient is 0.1 at 1200 N load, which is very close to the boundary lubrication regime. However, in the case of nano-oil II, the friction coefficient is

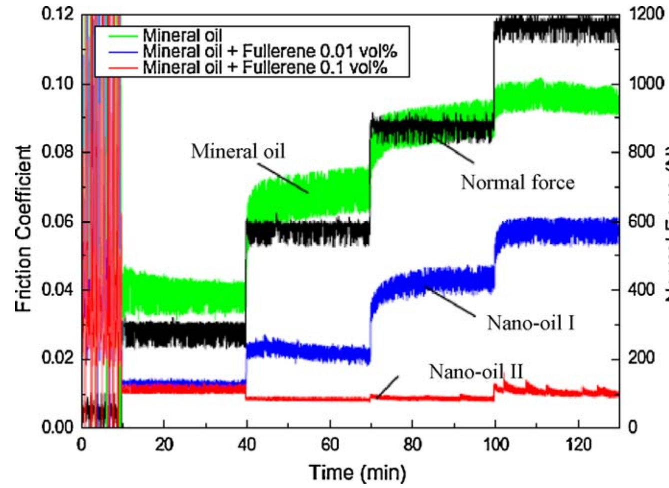

Fig. 12. Final results for friction coefficient in the steady state as a function of normal force, using the disk-on-disk type tribotester [71].

about 0.01 at 1200 N, maintaining the hydrodynamic lubrication regime [71].

6. Surface roughness

Table 4 shows the surface roughness of fixed plate operated at the orbiting speed of 1000 rpm and the normal force up to 1000 N for 100-min test period. The surface roughness of the fixed plate for raw mineral oil was distinctively high, 0.106 μm in depth at the scratched circle, while those of nano-oil I, II, III, and IV were 0.077, 0.067, 0.052, and 0.048 μm, respectively [72].

7. Energy performance

The refrigerator performance with the nanoparticles was investigated using energy consumption tests and freezer capacity tests by Ref. [69]. Authors reported that refrigerator's performance was better with 26.1% less energy consumption with 0.1% mass fraction of TiO_2 nanoparticles compared to the HFC134a and POE oil system. The same tests with Al_2O_3 nanoparticles showed that the different nanoparticles properties have little effect on the refrigerator energy performance. Thus, nanoparticles can be used in domestic refrigerators to considerably reduce energy consumption. Authors reported that there are two possible mechanisms by which the nanoparticles affect the refrigerator performance (i.e. energy and material compatibility performance). One is that some nanoparticles remain in the compressor to improve the compressor friction characteristic. The other reason is that some nanoparticles flow into the heat exchanger with the refrigerant to enhance the refrigerant heat transfer characteristics. However details of the mechanism have not been investigated.

Fu et al. [59] reported that nanoparticles may be effective to enhance the heat transfer of the refrigerant. One nanolubricant – a

Table 4
Surface roughness of the fixed plate measured by alpha-step at the rotating speed of 1000 rpm and the normal force up to 1000 N for 100-min test period [72].

Lubricant	Solvent	Fullerene fraction (vol%)	Surface roughness (μm)
Raw oil	Mineral oil	0	0.106
Nano-oil I	Mineral oil	0.01	0.077
Nano-oil II	Mineral oil	0.05	0.067
Nano-oil III	Mineral oil	0.1	0.052
Nano-oil IV	Mineral oil	0.5	0.048

Table 5
Energy consumption of HFC134a/POE oil and HFC134a/mineral oil/TiO_2 nanoparticles systems.

Mass fraction (%)	POE	0.06 TiO_2	0.1 Ti O_2	0.1 (50 days later)
Energy consumption (kWh/day)	1.077	0.849	0.796	0.800
Energy saving (%)		21.2	26.1	25.7

lubricant for chillers that incorporates a dispersion of nanometer-sized particles – has already been shown to improve the boiling heat flux by nearly 300% compared to the original nanoparticle-free refrigerant [60]. At the standard rating condition, the introduction of nanofluids gave rise to an increase in the COP by 5.15%, relative to a condition without nanofluids. Furthermore, the pressure drop penalty of the addition of nanofluids was almost negligible [73].

The data in Table 5 shows that the energy consumption of the system with nanoparticles was lower than that of the HFC134a and POE oil system. The energy consumption of 0.796 kWh/day was least at a nanoparticle mass fraction of 0.1%, which is 26.1% less than the POE oil system. In addition, the energy consumption was almost same after 50 days for the 0.1% mass fraction, which indicates that the refrigerator can work steadily for a long time.

8. Viscosity of nano-oil

Fig. 13 shows the kinematic viscosity of nano-oils as a function of volume fraction of fullerene nanoparticles in suspension for temperature ranging from 40 to 80 °C. There was no considerable change in the kinematic viscosity of nano-oil at the various volume fractions of nanoparticles, indicating that the kinematic viscosity of nano-oils is a weak function of oil temperature considered [72].

Fig. 14 shows the change of kinetic viscosity as a function of volume fraction and temperature of the oil. When particles are added, the increase rate of viscosity of the nano-oil is within 1%. In the temperature range for a compressor with time, the viscosity of the nano-oil is about the same as for the mineral oil, but the viscosity of the nano-oil increases by 7% at 20 °C in comparison with the mineral oil.

9. Pressure drop performance of nanorefrigerant

In the modern avenue of research, refrigerant-based nanofluids formed by suspension of nanoparticles in pure refrigerants have been used as a new kind of working fluid to improve the performance of refrigeration systems [68,69,74]. Presence of nanoparticles in suspension form may change the pressure drop characteristics of the fluid, so this characteristic needed to be understood in selecting the refrigerant. Liquid solid phase pressure drop characteristics and liquid solid and vapor phase (phase change) pressure drop characteristics of nanofluids are studied by different researchers. Li and Kleinstreuer [75] studied by simulation of the pressure drop characteristics of solid and liquid phase of fluid.

Pressure drop developed during the flow of coolant is one of the important parameters determining the efficiency of nanofluids application. Pressure drop and coolant pumping power are closely associated with each other. There are few properties which could influence the coolant pressure drop: density and viscosity. It is expected that coolants with higher density and viscosity experience higher pressure drop. This has contributed to the disadvantages of nanofluids application as coolant liquids. Yu et al. [35,36] and Lee et al. [35] investigated viscosity of water based Al_2O_3 nanofluids and ethylene glycol based ZnO nanofluids. Results clearly show, viscosity of nanofluids is higher than basefluid. Praveen et al. [76] in their numerical study reviewed that density of nanofluids is greater than basefluid. Both properties are found proportional with nanoparticles volume fraction. Several literatures have indicated that there is significant increase of nanofluids pressure drop compared to basefluid. Lee and Mudawar [77] revealed that single phase pressure drop of Al_2O_3 nanofluids in micro-channel heat sink increases with nanoparticles concentration. Vasu et al. [77,78] studied the thermal design of compact heat exchanger using nanofluids. In this study, it is found that pressure drop of 4% $Al_2O_3 + H_2O$ nanofluids is almost double of the basefluid. Pantzali et al. [79] reported there was substantial increase of nanofluids pressure drop and pumping power in plate heat exchanger. About 40% increase of pumping power was observed for nanofluids compared to water.

Peng et al. [80] reported that the frictional pressure drop of refrigerant-based nanofluids flow boiling inside the horizontal smooth tube is larger than that of pure refrigerant, and increases

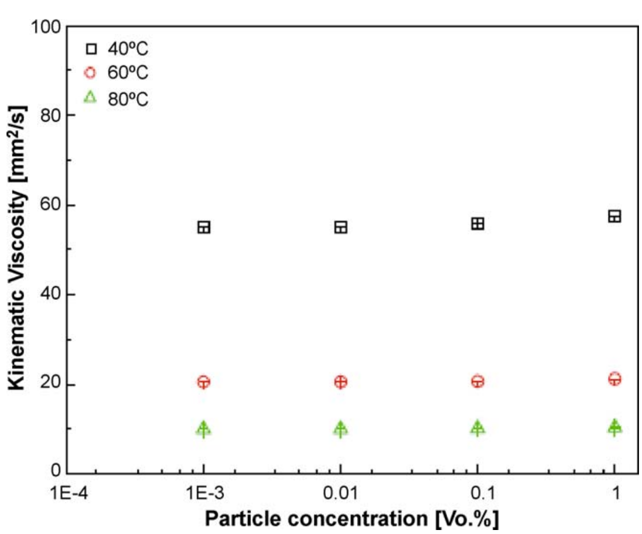

Fig. 13. Kinematic viscosity of nano-oils as a function of fullerene nanoparticle concentration and oil temperature ranging from 40 to 80 °C [72].

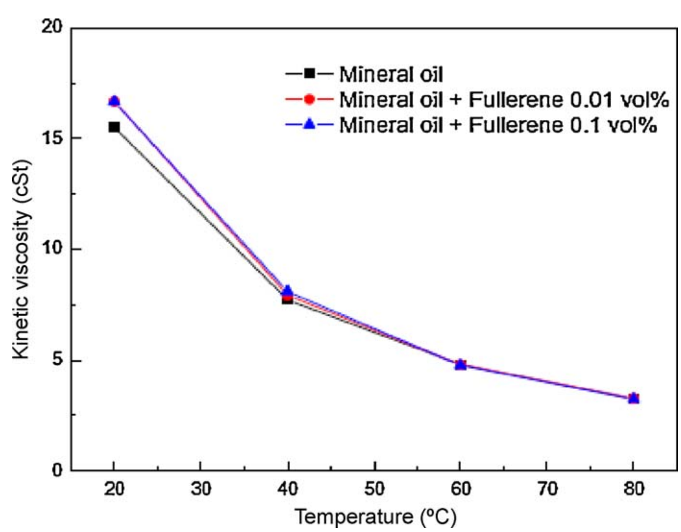

Fig. 14. Kinetic viscosity of fullerene-in-oil as a function of particle concentration and temperature [71].

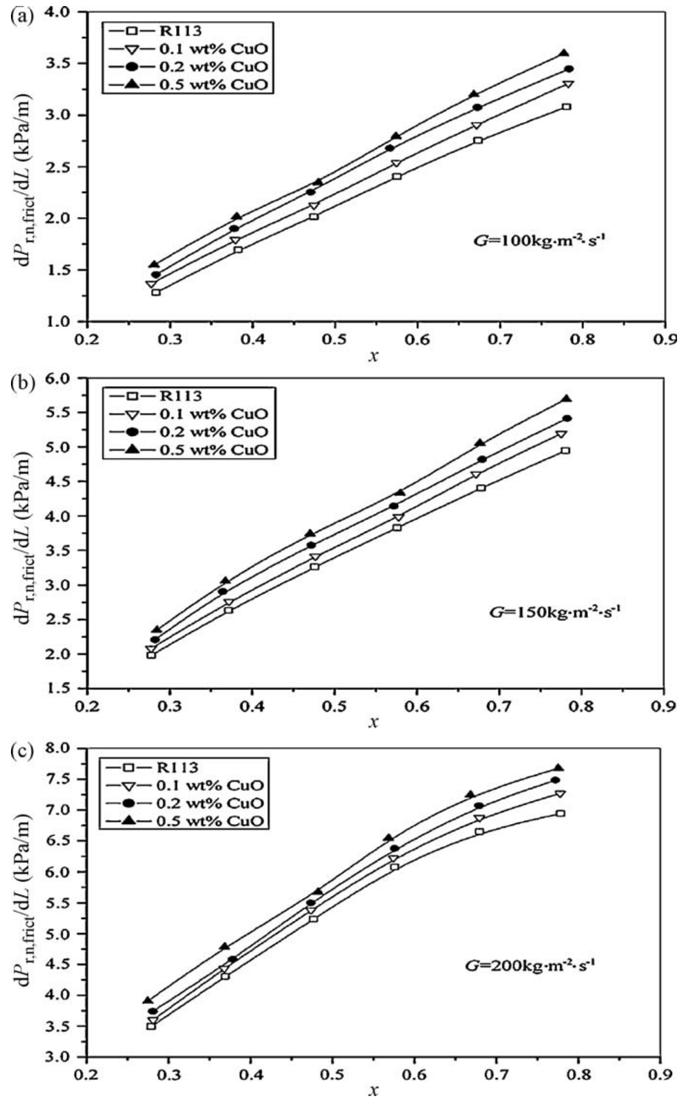

Fig. 15. Frictional pressure drop of CuO/R113 nanofluid versus local vapor quality at different mass fluxes (G): (a) $G = 100\ \mathrm{kg\ m^{-2}\ s^{-1}}$; (b) $G = 150\ \mathrm{kg\ m^{-2}\ s^{-1}}$; (c) $G = 200\ \mathrm{kg\ m^{-2}\ s^{-1}}$.

with the increase of the mass fraction of nanoparticles. The maximum increase of frictional pressure drop was found to be about 20.8% under the experimental conditions. Fig. 15 shows the pressure drop of nanorefrigerants with different concentrations and R113.

In Fig. 16 the total pressure drop P, measured inside the PHE, is plotted versus the cooling liquid volumetric flow rate for both the water and the nanofluid. Pantzali et al. [79] observed that the measured viscosity of the suspension (i.e. nanofluids) exhibits a

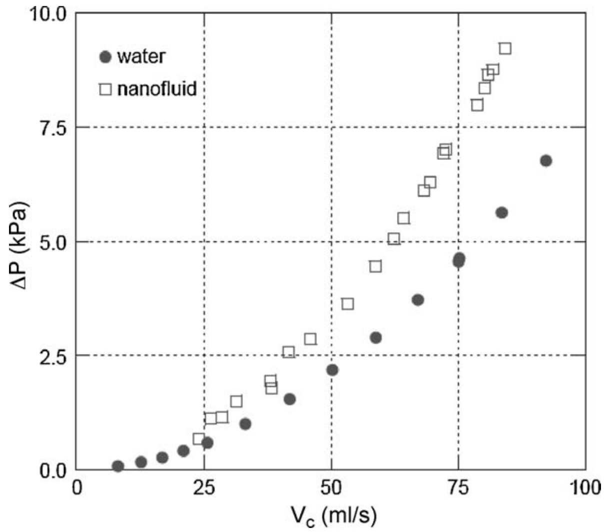

Fig. 16. Pressure drop of the cooling liquid inside the PHE versus the respective volumetric flow rate [79].

twofold increase compared to water. This leads to a significant increase in the measured pressure drop and consequently in the necessary pumping power when the nanofluids are applied. Authors calculated that the pumping power increased about 40% compared to water for a given flow rate. Authors observed that for a given heat duty the required volumetric flow rates for both the water and the nanofluid are practically equal, while the necessary pumping power in the case of the nanofluid is up to two times higher than the corresponding value for water due to the higher kinematic viscosity of the fluid [79].

An insignificant pressure drop penalty (within the experimental uncertainty) was found for all three volume fractions of CuO nanoparticles used in a study by [81]. Authors reported that nanofluids cause little or no penalty to pumping power because at very low concentrations the particles do not substantially affect viscosity.

With increasing heat flux, however, the enhancement was suppressed due to vigorous bubble generation. Fouling on the heat transfer surface was not observed during the course of this study. Experiments on solid and liquid phase pressure drop of CuO/H_2O nanofluid in micro-channel heat sink showed that the presence of nanoparticles causes a slight increase in pressure drop [82]. Experiments on pressure drop of TiO_2/H_2O nanofluid flowing upward through a vertical pipe showed that the pressure drop of nanofluid is slightly higher than that of the host fluid at a given Reynolds number [83]. Al_2O_3/H_2O nanofluid in micro-channel showed that the pressure drop of nanofluid is larger than that of the base fluid and increases with the increase of nanoparticle concentration at the same Reynolds number [77]. Li and Kleinstreuer [75] simulated the fully developed pressure gradient

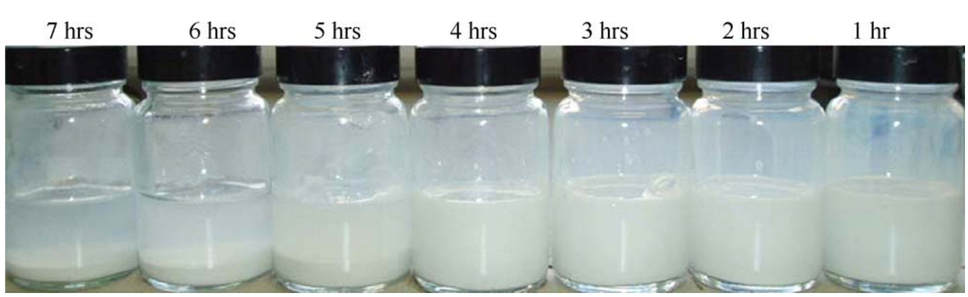

Fig. 17. Samples of Al_2O_3 nanofluids (without any stabilizer) stability change with time [88].

of CuO/H_2O nanofluid flow inside micro-channels. The simulation results show that (i) at a given Reynolds number, compared to the host fluid the pressure gradient increase are less than 2% and 5% at nanoparticle volume fractions of 1% and 4%, respectively and (b) compared to the host fluid at a given mean velocity the pressure gradient enhancement are less than 5% and 15% at nanoparticle volume fractions of 1% and 4%, respectively. Researchers show that the pressure drop at solid–liquid phase of nanofluid is larger than that of the host fluid and the increase of the pressure drop is related to the nanoparticle concentration.

Bartelt et al. [84] obtained insignificant effect on the phase change pressure drop of refrigerant/nanolubricant mixture (R134a/POE/CuO nanofluid) in flow boiling inside a horizontal tube. Significant pressure drop caused by lubricating oil overrules the detection of insignificant effect of nanoparticles in phase change nanofluid [85].

10. Binary nanofluids in absorption system

The binary mixture of NH_3/H_2O with nanoparticles of CNT or Al_2O_3 was used as a working fluid to investigate heat transfer performance along with the stability of nanorefrigerant by Ref. [86]. Authors reported that binary nanofluids are potential candidate for next generation working fluid of absorption systems [65]. Authors found that the heat transfer and absorption rate with 0.02 vol% CNT particles are about 17% and 16% higher than those without nanoparticles, respectively. Heat transfer and absorption rate with 0.02 vol% Al_2O_3 nanoparticles were 29% and 18% higher than those without nanoparticles, respectively. Authors recommended that the concentration of 0.02 vol% of Al_2O_3 nanoparticles be the best candidate for NH_3/H_2O absorption system.

11. Challenges of nanofluids

Many interesting properties of nanofluids have been reported in the review. In the previous studies, thermal conductivity has received the maximum attention, but many researchers have recently initiated studies on other thermo-physical properties as well. The use of nanofluids in a wide variety of applications appears promising. But the development of the field is hindered by (i) lack of agreement of results obtained by different researchers; (ii) poor characterization of suspensions; (iii) lack of theoretical understanding of the mechanisms responsible for changes in properties. Therefore, this paper highlighted several important issues that should receive greater attention in the near future

11.1. Long term stability of nanoparticles dispersion

Preparation of homogeneous suspension remains a technical challenge since the nanoparticles always form aggregates due to very strong van der Waals interactions. To get stable nanofluids, physical or chemical treatment have been conducted such as an addition of surfactant, surface modification of the suspended particles or applying strong force on the clusters of the suspended particles. Dispersing agents, surface-active agents, have been used to disperse fine particles of hydrophobic materials in aqueous solution [87].

On the other hand, if the heat exchanger operates under laminar conditions, the use of nanofluids seems advantageous, the only disadvantages so far being their high price and the potential instability of the suspension [84].

Generally, long term stability of nanoparticles dispersion is one of the basic requirements of nanofluids applications. Stability of nanofluids has good corresponding relationship with the enhancement of thermal conductivity where the better the dispersion behavior, the higher the thermal conductivity of nanofluids [88].

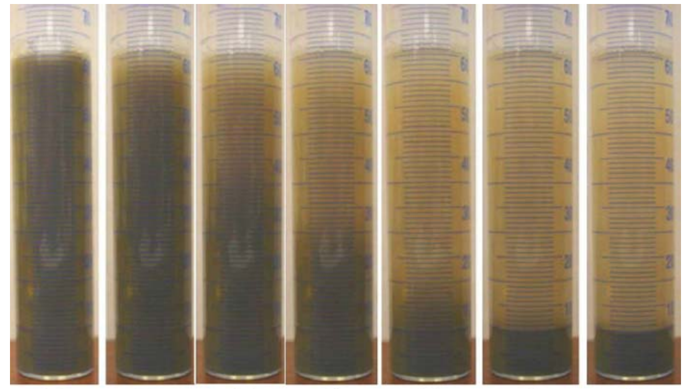

Fig. 18. The sedimentation of diamond nanoparticles at settling times of (a) 0 min, (b) 1 min, (c) 2 min, (d) 3 min, (e) 4 min, (f) 5 min, and (g) 6 min [8].

However the dispersion behavior of the nanoparticles could be influenced by period of time as can be seen in Figs. 17 and 18. As a result, thermal conductivity of nanofluids is eventually affected. Eastman et al. [24] revealed that, thermal conductivity of ethylene glycol based nanofluids containing 0.3% copper nanoparticles is decreased with time. In their study, the thermal conductivity of nanofluids was measured twice: first was within 2 days and second was 2 months after the preparation. It was found that fresh nanofluids exhibited slightly higher thermal conductivities than nanofluids that were stored up to 2 months. This might be due to reduced dispersion stability of nanoparticles with respect to time. Nanoparticles may tend to agglomerate when kept for long period of time. Lee and Mudawar [77] compared the Al_2O_3 nanofluids stability visually over time span. It was found that nanofluids kept for 30 days exhibit some settlement and concentration gradient compared to fresh nanofluids. It indicated that long term degradation in thermal performance of nanofluids could be happened. Particles settling must be examined carefully since it may lead to clogging of coolant passages.

Choi et al. [90] reported that the excess quantity of surfactant has a harmful effect on viscosity, thermal property, chemical stability, and thus it is strongly recommended to control the addition of the surfactant with great care. However, the addition of surfactant would make the particle surface coated, thereby resulting in the screening effect on the heat transfer performance of nanoparticles. Authors also mentioned that the surfactant may cause physical and/or chemical instability problems.

In contrast to other common base fluids such as water or ethylene glycol, a remarkably rapid agglomeration and settling of common nanoparticles was observed in refrigerants [81].

11.2. Higher viscosity

The viscosity of nanoparticle–water suspensions increases in accordance with increasing particle concentration in the suspension. Therefore, the particle mass fraction cannot be increased unlimitedly [91]. Jin et al. [65] concluded that in industrial heat exchangers, where large volumes of nanofluids are necessary and turbulent flow is usually developed, the substitution of conventional fluids by nanofluids seems inauspicious. Vassallo et al. [20] reported that the viscosity increased so rapidly with increasing particle loading that volume percentages of CNTs are limited to less than 0.2% in practical systems.

11.3. Lower specific heat

From the literatures, it is found that specific heat of nanofluids is lower than basefluid. Praveen et al. [76] reported that

CuO/ethylene glycol nanofluids, SiO_2/ethylene glycol nanofluids and Al_2O_3/ethylene glycol nanofluids exhibit lower specific heat compared to basefluids. An ideal refrigerant should possess higher value of specific heat which enable the refrigerant to remove more heat.

11.4. Thermal conductivity

The existing models for predicting thermal conductivities of CNT nanofluids, including Hamilton–Crosser model, Yu–Choi model and Xue model, cannot predict the thermal conductivities of CNT nanorefrigerants within a mean deviation of less than 15% [11].

11.5. High cost of nanofluids

Higher production cost of nanofluids is among the reasons that may hinder the application of nanofluids in industry. Nanofluids can be produced by either one-step or two-step methods. However both methods require advanced and sophisticated equipments. Lee and Mudamawar [77] and Pantzali et al. [77,79] stressed that high cost of nanofluids is among the drawback of nanofluids applications.

11.6. Difficulties in production process

Previous efforts to manufacture nanofluids have often employed either a single step that simultaneously makes and disperses the nanoparticles into base fluids, or a two-step approach that involves generating nanoparticles and subsequently dispersing them into a base fluid. Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange. Furthermore, the base fluids contain other ions and reaction products that are difficult or impossible to separate from the fluids.

Another difficulty encountered in nanofluid manufacture is nanoparticles' tendency to agglomerate into larger particles, which limits the benefits of the high surface area nanoparticles. To counter this tendency, particle dispersion additives are often added to the base fluid with the nanoparticles. Unfortunately, this practice can change the surface properties of the particles, and nanofluids prepared in this way may contain unacceptable levels of impurities. Most studies to date have been limited to sample sizes less than a few hundred milliliters of nanofluids. This is problematic since larger samples are needed to test many properties of nanofluids and, in particular, to assess their potential for use in new applications [92].

Yet the fact that nanofluids have more points in favor of them than against, for usage as cooling fluid, has emerged as an undisputed view. This calls for a more intensified effort in the research on nanofluids. In contrast to the traditional unilateral approach, this research needs to examine closely a variety of issues, such as synthesis, characterization, thermo-physical properties, heat and mass transport, modeling, and device- as well as system-level applications. Hence, a multi-disciplinary approach comprising researchers such as thermal engineers, chemical technologists, material scientists, chemists, and physicists needs to be undertaken. Only such an approach can ensure a "cooler future" with nanofluids [93].

11.7. Fouling

Even though many nanoparticles were applied to the single phase heat transfer of water, actual heat transfer improvement was not yet reported. Furthermore, when these particles were applied to the boiling heat transfer, they even caused fouling on heat transfer surface and consequently HTCs were decreased [14,20,94].

12. Conclusions

- Based on the literatures, it has been found that the thermal conductivities of nanorefrigerants are higher than traditional refrigerants. It was also observed that increased thermal conductivity of nanorefrigerants is comparable with the increased thermal conductivities of other nanofluids.
- Thermal conductivities of refrigerant with carbon CNT found to be higher than refrigerant without CNT. It was observed that maximum thermal conductivity enhancement was found to be about 46%. It was also observed that thermal conductivities of nanorefrigerants depend on concentrations and aspect ratio of CNT.
- It has been observed that heat transfer enhancement can be achieved from a minimum value of 21% to a maximum value of 275% using nanorefrigerants compared to traditional refrigerants. However, many researchers Das et al., Bang and Chang and Sobhan and Peterson [14,21,95] found that pool boiling performance is deteriorated for different concentrations and types of nanofluids.
- The refrigerator's performance was found 26.1% better with 0.1% mass fraction of TiO_2 nanoparticles compared to a refrigerator's performance with the HFC134a and POE oil system [56].
- The mineral lubricant with Al_2O_3 nanoparticles (0.05, 0.1, and 0.2 wt%) was used to investigate the lubrication and heat transfer performance. Results indicated that the 60% R134a and 0.1 wt% Al_2O_3 nanoparticles provided optimal performance. Under these conditions, the power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%.
- The friction coefficient of nano-oil IV shows $\sim$0.02, which is the lowest friction coefficient among various nano-oils studied by Ref. [72]. Surface roughness of this oil with refrigerant oil was found to be a minimum value of 0.048 μm compared to other oils [72].
- Several literatures have indicated that there is significant increase of nanofluids pressure drop compared to basefluid. Lee and Mudawar [77] revealed that single phase pressure drop of Al_2O_3 nanofluids in micro-channel heat sink increases with nanoparticles concentration. Vasu et al. [77,78] studied the thermal design of compact heat exchanger using nanofluids and found that pressure drop of 4% $Al_2O_3 + H_2O$ nanofluids is almost double of the basefluid. Pantzali et al. [79] reported there was substantial increase of nanofluids pressure drop and pumping power in plate heat exchanger and found about 40% increase in pumping power for nanofluids compared to water. Peng et al. [80] reported that the frictional pressure drop of refrigerant-based nanofluids flow boiling inside the horizontal smooth tube is larger than that of pure refrigerant, and increases with the increase of the mass fraction of nanoparticles. The maximum increase of frictional pressure drop was found to be about 20.8% under the experimental conditions.
- It was also found that there are inconsistencies in the reported results published by many researchers. Few researchers reported the inconsistencies between model and experimental results of thermal conductivity of nanofluids.
- Exact mechanism of enhanced heat transfer for nanofluids is still unclear as reported by many researchers.
- However, it should be noted that many challenges need to be identified and overcome for different applications.
- Nanofluids stability and its production cost are major factors that hinder the commercialization of nanofluids. By solving these challenges, it is expected that nanofluids can make substantial impact as coolant in heat exchanging devices.

13. Recommendations for future work

The heat transfer results show that nanofluids have significant potential for improving the flow boiling heat transfer of refrigerant/lubricant mixtures. However, the reasons behind this marked improvement with nanoparticle volume fractions at different concentrations are not clearly understood. It is unclear why a large increase in heat transfer is observed with an insignificant increase in pressure. Moreover, obvious challenges with particle circulation and unknown effects on the compressor of an air conditioning or refrigeration system have not been addressed. Nevertheless, the present findings are compelling and further research should be undertaken [81].

Future research is required to investigate the influence of the particle material, its shape, size, distribution, and concentration on refrigerant boiling performance.

Experimental results on the fundamental properties such as specific heat, density, and viscosity of nanofluids are very limited in the literatures. There are potentials to explore research to determine these properties experimentally.

Acknowledgements

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References

[1] Choi SUS. Development and applications of Non-Newtonian flows'. In: Singer DA, Wang HP, editors. Development and application of non-Newtonian flows. Vol. FED 231. New York: ASME; 1995.
[2] Serrano E, Rus G, Martínez JG. Nanotechnology for sustainable energy. Renewable and Sustainable Energy Reviews 2009;13(9):2373–84.
[3] Elcock D. Potential impacts of nanotechnology on energy transmission applications and needs. Environmental Science Division, Argonne National Laboratory; 2007.
[4] Hindawi, Special issue on heat transfer in nanofluids; 2009.
[5] Eastman JA, Choi US, Thompson LJ, Lee S. Enhanced thermal conductivity through the development of nanofluids. Mater Res Soc Symp Proc 1996;457:3–11.
[6] Liu MS, Lin MCC, Huang IT, Wang CC. Enhancement of thermal conductivity with CuO for Nanofluids. Chemical Engineering and Technology 2006; 29(1):72–7.
[7] Duangthongsuk W, Wongwises S. An experimental study on the heat transfer performance and pressure drop of TiO_2–water nanofluids flowing under a turbulent flow regime. International Journal of Heat and Mass Transfer 2010;53(1–3):334–44.
[8] Trisaksri V, Wongwises S. Nucleate pool boiling heat transfer of TiO_2–R141b nanofluids. International Journal of Heat and Mass Transfer 2009;52(5–6):1582–8.
[9] Paul G, Chopkar M, Manna I, Das PK. Techniques for measuring the thermal conductivity of nanofluids: a review. Renewable and Sustainable Energy Reviews 2010;14(7):1913–24.
[10] Godson L, Raja, Mohan LD, Wongwises S. Enhancement of heat transfer using nanofluids—an overview. Renewable and Sustainable Energy Reviews 2010;14(2):629–41.
[11] Jiang W, Ding G, Peng H. Measurement and model on thermal conductivities of carbon nanotube nanorefrigerants. International Journal of Thermal Sciences 2009;48:1108–15.
[12] Park KJ, Jung DS. Enhancement of nucleate boiling heat transfer using carbon nanotubes. International Journal of Heat and Mass Transfer 2007;50:4499–502.
[13] Park KJ, Jung DS. Boiling heat transfer enhancement with carbon nanotubes for refrigerants used in building air conditioning. Energy and Buildings 2007; 39(9):1061–4.
[14] Das SK, Putra N, Roetzel W. Pool boiling characteristics of nano fluids. International Journal of Heat and Mass Transfer 2003;46:851–62.
[15] Das SK, Putra N, Roetzel W. Pool boiling of nano-fluids on horizontal narrow tubes. International Journal of Multiphase Flow 2003;29:1237–47.
[16] Witharana S. Boiling of refrigerants on enhanced surfaces and boiling of nanofluids. Stockholm, Sweden: Royal Institute of Technology; 2003.
[17] You MS, Kim JH. Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer. Applied Physics Letters 2003;83(16):3374–6.
[18] Kim JH, Kim KH, You MS. Pool boiling heat transfer in saturated nanofluids. In: Proceeding of ASME international mechanical engineering congress and exposition; 2004.p. 621–8.
[19] Tu JP, Nam D, Theo T. An experimental study of nanofluid boiling heat transfer. In: The 6th international symposium on heat transfer; 2004.p. 15–9.
[20] Vassallo P, Kumar R, Amico S. Pool boiling heat transfer experiments in silica–water nanofluids. International Journal of Heat and Mass Transfer 2004; 47:407–11.
[21] Bang IC, Chang SH. Boiling heat transfer performance and phenomena of Al_2O_3–water nanofluids from a plain surface in a pool. International Journal of Heat and Mass Transfer 2005;48:2407–19.
[22] Moreno Jr G, Oldenburg S, You SM, Kim JH. Pool boiling heat transfer of alumina–water, zinc oxide–water and alumina–water + ethylene glycol nanofluids. In: Proceedings of ASME summer heat transfer conference; 2005. p. 625–32.
[23] Wen DS, Ding YL. Experimental investigation into the pool boiling heat transfer of aqueous based γ-alumina nanofluids. Journal of Nanoparticle Research 2005;7:265–74.
[24] Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. Applied Physics Letters 2001;78(6):718–20.
[25] Hwang YJ, Ahn YC, Shin HS, Lee CG, Kim GT, Park HS, et al. Investigation on characteristics of thermal conductivity enhancement of nanofluids. Current Applied Physics 2006;6(6):1068–71.
[26] Yoo D-H, Hong KS, Yang H-S. Study of thermal conductivity of nanofluids for the application of heat transfer fluids. Thermochimica Acta 2007;455(1–2):66–9.
[27] Choi SUS, Zhang ZG, Yu W, Lockwood FE, Grulke EA. Anomalous thermal conductivity enhancement in nanotube suspensions. Applied Physics Letters 2001;79(14):2252–4.
[28] Yang Y. Carbon nanofluids for lubricant application. University of Kentucky; 2006.
[29] Jana S, Salehi-Khojin A, Zhong W-H. Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives. Thermochimica Acta 2007;462(1–2):45–55.
[30] Kang HU, Kim SH, Oh JM. Estimation of thermal conductivity of nanofluid using experimental effective particle. Experimental Heat Transfer 2006; 19(3):181–91.
[31] Zhang X, Gu H, Fujii M. Experimental study on the effective thermal conductivity and thermal diffusivity of nanofluids. International Journal of Thermophysics 2006;27(2):569–80.
[32] Zhang X, Gu H, Fujii M. Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. Journal of Applied Physics 2006;100(4):p044325.
[33] Zeinali Heris S, Nasr Esfahany M, Etemad SG. Experimental investigation of convective heat transfer of Al_2O_3/water nanofluid in circular tube. International Journal of Heat and Fluid Flow 2007;28(2):203–10.
[34] Timofeeva EV, Gavrilov AN, McCloskey JM, Tolmachev YV, Sprunt S, Lopatina LM, et al. Thermal conductivity and particle agglomeration in alumina nanofluids: experiment and theory. Physical Review E 2007;76(6):p16.
[35] Lee J-H, Hwang KS, Jang SP, Lee BH, Kim JH, Choi SUS, et al. Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al_2O_3 nanoparticles. International Journal of Heat and Mass Transfer 2008;51(11–12):2651–6.
[36] Yu W, France DM, Choi SUS, Routbort JL. Argonne National Laboratory review and assessment of nanofluid technology for transportation and other applications. Energy Systems Division; 2007.
[37] Vajjha RS, Das DK. Experimental determination of thermal conductivity of three nanofluids and development of new correlations. International Journal of Heat and Mass Transfer 2009;52(21–22):4675–82.
[38] Leong KY, Saidur R, Kazi SN, Mamun MA. Performance investigation of an automotive car radiator operated with nanofluid based coolants (nanofluid as a coolant in a radiator). Applied Thermal Engineering 2010. doi: 10.1016/j.applthermaleng, 2010.07.019.
[39] Shen B. Minimum quantity lubrication grinding using nanofluids. USA: University of Michigan; 2006.
[40] Wen D, Lin G, Vafaei S, Zhang K. Review of nanofluids for heat transfer applications. Particuology 2009;7(2):141–50.
[41] Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. International Journal of Heat and Mass Transfer 2000;43(19):3701–7.
[42] Choi SUS, Yu W, Hull JR, Zhang ZG, Lockwood FE. Nanofluids for vehicle thermal management. Society of Automotive Engineers 2001-01-1706; 2001 . pp. 139–144.
[43] Keblinski P, Nayak SK, Zapol P. Charge distribution and stability of charged carbon nanotubes. Physical Review Letters 2002;89(25).
[44] Xuan Y, Li Q. Heat transfer enhancement of nanofluids. International Journal of Heat and Fluid Flow 2000;21:58–64.
[45] Hong TK, Yang HS, Choi CJ. Study of the enhanced thermal conductivity of Fe nanofluids. Journal of Applied Physics 2005;97(6).
[46] Patel HE, Das SK, Sundararajan T. Thermal conductivities of naked and monolayer protected metal nanoparticle based nanofluids: Manifestation of anomalous enhancement and chemical effects. Applied Physics Letters 2003; 83(14):2931–3.
[47] Masuda H. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles (dispersion of y-$A1_2O_3$, SiO_2, and TiO_2 ultra-fine particles). Netsu Bussei 1993;4:227–33.
[48] Lee S. Measuring thermal conductivity of fluids containing oxide nanoparticles. ASME Journal of Heat Transfer 1999;121(2):280–9.
[49] Xie H. Thermal conductivity enhancement of suspensions containing nanosized alumna particles. Journal of Applied Physics 2002;91:4568–72.

[50] Zhou LP, Wang BX. Experimental research on the thermophysical properties of nanoparticle suspensions using the quasi-steady method. Annual Proceedings of Chinese Engineering Thermophysics 2002;889–92.
[51] Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO_2–water based nanofluids. International Journal of Thermal Sciences 2005;44(4):367–73.
[52] Xie H. Nanofluids containing multiwalled carbon nanotubes and their enhanced thermal properties. Journal of Applied Physics 2003;94(8):4967–71.
[53] Assael MJ. Thermal conductivity of suspensions of carbon nanotubes in water. International Journal of Thermophysics 2004;25(4):971–85.
[54] Hao P, Guoliang D, Weiting J, Haitao H, Yifeng G. Heat transfer characteristics of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube. International Journal of Refrigeration 2009;32:1259–70.
[55] Wu XM, Li P, Li H, Wang WC. Investigation of pool boiling heat transfer of R11 with TiO_2 nano-particles. Journal of Engineering Thermophysics 2008;29(1): 124–6.
[56] Hao P, Guoliang D, Haitao H, Weiting J, Dawei Z, Kaijiang W. Nucleate pool boiling heat transfer characteristics of refrigerant/oil mixture with diamond nanoparticles. International Journal of refrigeration 2010;33:347–58.
[57] Wang KJ, Ding GL, Jiang WT. Nano-scale thermal transporting and its use in engineering. In: Proceedings of the 4th symposium on refrigeration and air condition; 2006. p. 66–75.
[58] Li P, Wu XM, Li H. Pool boiling heat transfer experiments of refrigerants with nanoparticle TiO_2. In: Proceedings of the 12th symposium on engineering thermophysics; 2006. p. 325–8.
[59] Fu L, Wang R, Cong W, Li Q, Wu Y. Experiment study on performance of refrigerator using nano-particle additive. Journal of Xi'an Jiaotong University 2008;42:852–4.
[60] http://www.nano.gov/html/research/Achievements_pdf/02-Energy/Nanoparticlesdramaticallyimprovechillerefficiency_nist.pdf, Access date: 27/03/2010.
[61] Kedzierski MA. Effect of CuO nanoparticle concentration on R134a/lubricant pool-boiling heat transfer. Journal of Heat Transfer 2009;131(4):p7.
[62] Peng H, Ding G, Jiang W, Hu H, Gao Y. Heat transfer characteristics of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube. International Journal of Refrigeration 2009;32:1259–70.
[63] Kedzierski MA, Gong M. Effect of CuO nanolubricant on R134a pool boiling heat transfer with extensive measurement and analysis details. USA: NISTIR 7336, National Institute of Standards and Technology; 2007.
[64] Bi S, Shi L. Experimental investigation of a refrigerator with a nano-refrigerant Qinghua Daxue Xuebao. Journal of Tsinghua University 2007;47(11):2002–5.
[65] Jin KL, Junemo K, Hiki H, Yong TK. The effects of nanoparticles on absorption heat and mass transfer performance in NH_3/H_2O binary nanofluids. International Journal of Refrigeration 2010;33:269–75.
[66] Naphon P, Thongkum D, Assadamongkol P. Heat pipe efficiency enhancement with refrigerant–nanoparticles mixtures. Energy Conversion and Management 2009;50:772–6.
[67] Putnam SA, Cahill DG, Braun PV, Ge ZB, Shimmin RG. Thermal conductivity of nanoparticle suspensions. Journal of Applied Physics 2006;99(8).
[68] Wang RX, Xie HB. A refrigerating system using HFC134a and mineral lubricant appended with n-TiO_2(R) as working fluids. In: Proceedings of the 4th International Symposium on HAVC; 2003. p. 888–92.
[69] Bi SS, Shi L, Zhang LL. Application of nanoparticles in domestic refrigerators. Applied Thermal Engineering 2008;28:1834–43.
[70] Lee J, Cho S, Hwang Y, Cho H-J, Lee C, Choi Y, et al. Application of fullerene-added nano-oil for lubrication enhancement in friction surfaces. Tribology International 2009;42:440–7.
[71] Lee K, Hwang Y, Cheong S, Kwon L, Kim S, Lee J. Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. Current Applied Physics 2009;9:128–31.
[72] Jaekeun L, Sangwon C, Yujin H, Changgun L, Soo HK. Enhancement of lubrication properties of nano-oil by controlling the amount of fullerene nanoparticle additives. Tribology Letters 2007;28:203–8.
[73] Performance augmentation of a water chiller system using nanofluids. Free-library; 2010.
[74] Wang KJ, Shiromoto K, Mizogami T. Experimental study on the effect of nano-scale particle on the condensation process. In: Proceedings of the 22nd international congress of refrigeration; 2007.
[75] Li J, Kleinstreuer C. Thermal performance of nanofluid flow in microchannels. International Journal of Heat and Fluid Flow 2008;29:1221–32.
[76] Praveen K, Namburu DK, Das KM, Tanguturi, Ravikanth SV. Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties. International Journal of Thermal Sciences 2009;48:290–302.
[77] Lee J, Mudawar I. Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels. International Journal of Heat and Mass Transfer 2007;50(3–4):452–63.
[78] Vasu V, Rama Krishna K, Kumar ACS. Heat transfer with nanofluids for electronic cooling. International Journal of Materials and Product Technology 2009;34(1/2):158–71.
[79] Pantzali MN, Mouza AA, Paras SV. Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE). Chemical Engineering Science 2009;64:3290–300.
[80] Peng H, Ding G, Jiang W, Hu H, Gao Y. Measurement and correlation of frictional pressure drop of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube. International Journal of Refrigeration 2009;32:1756–64.
[81] Kristen H, Young GP, Liping L, Anthony MJ. Flow-boiling heat transfer of R-134a-based nanofluids in a horizontal tube. International Journal of Heat and Mass Transfer 2010;53:944–51.
[82] Chein R, Chuang J. Experimental microchannel heat sink performance studies using nanofluids. International Journal of Thermal Sciences 2007;46:57–66.
[83] He YR, Jin Y, Chen HS, Ding YL, Chang DQ, Lu HL. Heat transfer and flow behavior of aqueous suspensions of TiO_2 nanoparticles (nanofluids) flowing upward through a vertical pipe. International Journal of Heat and Mass Transfer 2007;50:2272–81.
[84] Bartelt K, Park YG, Liu LP, Jacobi AM. Flow-boiling of R-134a/POE/CuO nanofluids in a horizontal tube. In: Proceeding of the international refrigeration and air conditioning conference; 2008.
[85] Zurcher O, Thome JR, Favrat D. Flow boiling and pressure drop measurements for R-134a/oil mixtures. Part 2. Evaporation in a plain tube. HVAC&R Research 1997;3(1):54–64.
[86] Kim D, Kwon Y, Cho Y, Li C, Cheong S, Hwang Y, Lee J, Hong D, Moon S. Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions. Current Applied Physics 2009;9(2 (Suppl. 1)):pe119–e123.
[87] Hwang Y, Par HSK, Lee JK, Jung WH. Thermal conductivity and lubrication characteristics of nanofluids. Current Applied Physics 2006;6S1:e67–71.
[88] Guoliang D, Hao P, Weiting J, Yifeng G. The migration characteristics of nanoparticles in the pool boiling process of nanorefrigerant and nanorefrigerant–oil mixture. International Journal of Refrigeration 2009;32: 114–23.
[90] Choi C, Yoo HS, Oh JM. Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants. Current Applied Physics 2008;8:710–2.
[91] Wu S, Zhu D, Li X, Li H, Lei J. Thermal energy storage behavior of Al_2O_3–H_2O nanofluids. Thermochimica Acta 2009;483:73–7.
[92] The energy lab. NETL; 2009.
[93] Sarit KD. Nanofluids—the cooling medium of the future. Heat Transfer Engineering 2006;27(10):1–2.
[94] Bang IC, Chang SH. Boiling heat transfer performance and phenomena of Al_2O_3–water nano fluids from a plain surface in a pool. In: Proceedings of the ICAPP; 2004. p. 1–7.
[95] Sobhan CB, Peterson GP. Microscale and nanoscale heat transfer: fundamentals and engineering applications. CRC Press, Taylor and Francis Group; 2008